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14. ABSTRACT
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PaveMend™ as a Solution for Rapid Runway Repair

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Abstract

The paper first gives definition and historical perspective to the problem of Rapid Runway Repair (RRR), particularly its roots in the area of expedient runway construction. The differences in Cold War and post-Cold War RRR needs are also discussed. CeraTech, Inc.'s *PaveMend*™ is presented as a good solution for post-Cold War RRR needs, which are speed of the repair and durability of the repair. The homogeneous nature of *PaveMend*™ is illustrated by a photomicrograph, and the ability of *PaveMend*™ to be engineered to match the material to be repaired is discussed as a desirable quality. A manufacturer's specification sheet with independent, third-party lab results is presented, which illustrates the ability of *PaveMend*™ to mimic the properties of a typical runway which might need RRR in the post-Cold War era.

Different formulations of *PaveMend*™ are briefly discussed, but the paper focuses on the "RRR formulation" of *PaveMend*™, which utilizes fly ash, a pozzolan, as its reactive material. Differences between pozzolans and Portland cement are discussed, highlighting those properties which have a positive impact on the durability of repairs. In addition, a table is presented which highlights important differences between *PaveMend*™ and a typical high-early set material.

Results from preliminary testing by the Air Force Research Laboratory (ARFL)[3] is presented, which includes density measurements, as well as time histories of heat of hydration, compressive strength, flexural strength, sonic modulus of elasticity, and bonding strength. In addition, a successful field demonstration of *PaveMend*™ as a RRR material is briefly described.

Disclaimer

While this paper presents results from testing of *PaveMend*™ by the Air Force Research Laboratory (AFRL), any conclusions or opinions offered herein are attributable to the authors, and should not be construed as an official endorsement of *PaveMend*™ by the United States Air Force or by AFRL.

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[3] The term AFRL, as used throughout this paper, refers specifically to AFRL / MLQD, the Deployed Base Systems Branch of AFRL, which is physically located at Tyndall AFB, Florida (HQ AFRL is located at Wright-Patterson AFB, Ohio).

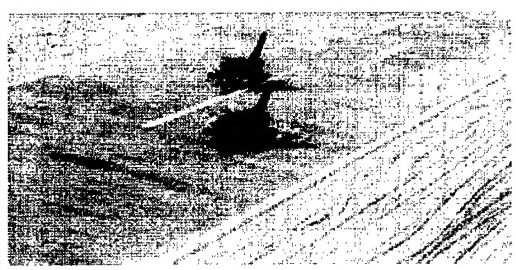
Introduction to Rapid Runway Repair (RRR) *(Dover, et al., 2002)*

Background. Military aircraft are the most vulnerable when they are on the ground, so in any major armed conflict, one of the first targets of aggression is runways. As clearly demonstrated in recent conflicts, air superiority is a critical component in modern warfare. When airfields are attacked, and runways damaged, the primary mission of the military engineer is usually Rapid Runway Repair (RRR).

World War II. The roots of RRR can be traced to World War II developments aimed at expedient runway construction. After initial attempts at expediently constructing wooden-plank runways failed, three primary matting materials were developed for expedient construction of runways. The mat types were Pierced Steel Planking (PSP) (shown in Figure 1a), Hessian Matting, and Square Mesh Track (SMT). Each type had advantages and disadvantages, and sometimes the three types were made into a "sandwich" to use the advantage of each (while minimizing the disadvantages).

Cold War. After World War II, the Cold War began, and the United States was faced with defending "permanent" air bases around the world. Along with the already identified need for expedient construction, the need for RRR soon became apparent. Two major factors highlighted the need for RRR capability: (1) the advances in modern weaponry, which generally made runways more vulnerable; and (2) the use of sabotage as an offensive weapon in places like Korea and Viet Nam. An aluminum structural matting called "AM-2" was developed for expedient construction (see Figure 1b), but was additionally used for RRR, as were precast slab replacement panels. Recently, folded fiberglass mats (FFMs) have been used for RRR, serving as FOD (i.e., foreign object damage) covers over repaired craters on aircraft operating surfaces. In general, the Cold War threat was for a runway to be damaged, either by attack or sabotage, for the express purpose of keeping Allied planes on the ground (where they are most vulnerable). Therefore, Cold War RRR methods focused on being able to get planes into the air as soon as possible after an attack.

(a) Pierced Steel Planking (PSP) being installed at night by men of the IX Engineer Command at an Air Force Base in Germany (circa 1945).



(b) Fighters land on a 2.7 km (9,000 ft) runway constructed of AM-2 matting at Tuy Hoa Air Base, Republic of South Vietnam (circa 1968).

Figure 1. Expedient construction, the ancestor of modern Rapid Runway Repair

Post–Cold War. While RRR in the Cold War era focused on the threat of Allied bases being attacked, i.e., our own runways being bombed, recent experience has suggested that the post-Cold War world will require a different type of RRR. In recent conflicts, the air superiority of Allied forces has prevented calamitous runway damage from occurring on Allied runways, but the converse has not been true. The more likely RRR threat, in the post-Cold War era, is the need to repair a runway that Allied forces have damaged, then captured. (Unfortunately for the military engineer tasked with this type

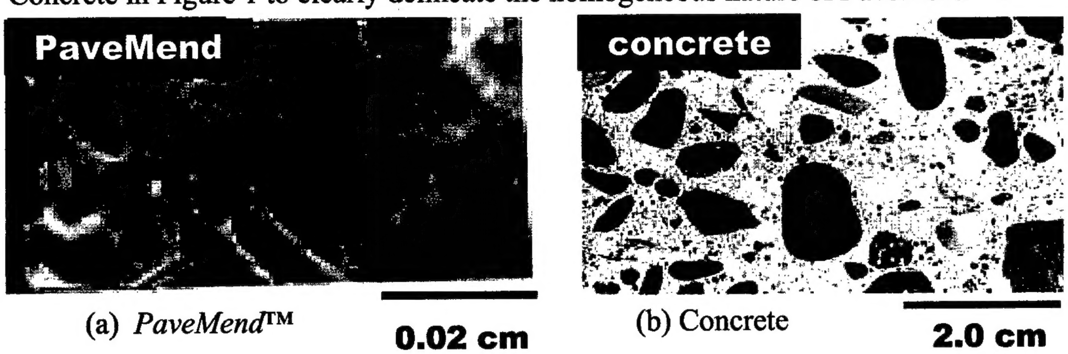
of repair, the United States Air Force does an excellent job of making an enemy airfield impassible and/or unuseable.) In fact, some researchers have started using the term Airfield Damage Repair (ADR) for this type of recovery, to distinguish it from "traditional" Cold War-era RRR. While traditional RRR focused almost exclusively on speed of the repair, post-Cold War RRR must deliver both speed and durability: speed of the repair so that transport planes can start landing as soon as possible; and durability so that the repairs will last as the base is used for ongoing military operations.

The Proposed Solution

Background on PaveMend™. Ceratech, Inc. has developed a family of rapid repair materials for a wide range of repair applications. Known collectively as *PaveMend™*,[4] these are non-traditional cementitious materials that do not contain Portland Cement and utilize a very high percentage (up to 70% by weight) of residual materials, including but not limited to:

- Fly ash
- Bio-solids ash
- Volcanic ash
- Mine tailings
- Crushed glass
- Dredge materials
- Municipal solid waste (MSW) ash

Homogeneous nature of PaveMend™. *PaveMend™* mixes utilize no conventional aggregate, but instead are comprised of very fine grains of metal oxides that exhibit chemical bonding to themselves, to neighboring concrete, and to metal structures. A photomicrograph of *PaveMend™* is compared to a photograph of a Portland Cement Concrete in Figure 1 to clearly delineate the homogeneous nature of *PaveMend™*.



(a) *PaveMend™* (b) Concrete

Figure 2. Homogeneous *PaveMend™* versus non-homogeneous concrete[5]

PaveMend™ is not like traditional concrete. The typical high performance concrete uses highly specified, non-renewable virgin aggregates, tightly controlled Portland cement, and potable (i.e., drinking quality) water. Special performance properties are achieved by the use of admixtures (air entrainment, plasticity, early set, rapid cure, etc.). In sharp contrast, *PaveMend™* materials utilize renewable, recycled (i.e., recovered) waste materials and non-problematic chemical activators, and it can tolerate non-potable water (even seawater). Performance properties are achieved by the formulation without need for extraneous admixtures. Conceptual equations which summarize the systematic differences PaveMend and traditional concrete are shown in Table 1.

PaveMend™ repairs match original material. Key to the benefits of *PaveMend™* are

[4] Early versions of *PaveMend™* were also referred to as CeraCrete.

[5] Note the difference in scale between the photomicrograph of *PaveMend™* and the photograph of Portland cement concrete, that is:

$$(\textit{PaveMend}^{\text{TM}} \text{ scale}) \approx (100) * (\text{concrete scale})$$

Traditional Concrete				
Non-reactive Ingredients (Sand and Rock)	+	Binder (Portland cement)	=	Concrete (Multi-component)
***PaveMend*™**				
Reactive Ingredients (Waste minerals)	+	Activator (Chemical Agents)	=	*PaveMend*™ (Homogeneous)

Table 1. Conceptual equations for Traditional Concrete and *PaveMend*™

its "engineered" mechanical properties, which allow customized mixes to be developed which have compatible structural properties (compared to the existing concrete to be repaired). Conversely, many traditional high-performance materials are designed to have extremely high strength in order to meet specific rapid set criteria. As a result, these materials usually have a correspondingly high modulus of elasticity, which means that there is a significant mismatch in the properties of the existing material and the repair material. If the repair bond is strong enough, the original material may fail in the vicinity of the repair, simply because of the mismatch in material properties. Too often, this is touted by vendors as a success for the repair material (i.e., it is "stronger than the original material"), but the more ideal repair is one which conforms the repair material to the original material, creating a near monolithic structure.

PaveMend*™ *as a RRR material. The *PaveMend*™ formulation used for RRR has properties very similar to a fully-cured, high-quality, Portland cement concrete runway, as demonstrated by the manufacturer's specification sheet (see Table 2). All of the data in Table 2 was generated by third party, independent test laboratories (testing by AFRL is reported separately, in a subsequent section of this paper).

The RRR version of *PaveMend*™ is actually available in two different formulations: *PaveMend*™ 5.0 and *PaveMend*™ 15.0, where the formulations have 5 and 15 minutes of workability, respectively. The RRR formulation of *PaveMend*™ uses fly ash as the primary reactive ingredient. The importance of fly ash, a pozzolan, in the properties of the repair matrix is of specific interest, and is discussed at length in the following section.

What is a pozzolan?

Basic cement types. While there are some variations, cements can generally be separated into two major groups: "manufactured" cements and "natural" cements. The primary type of manufactured cement is Portland cement. The primary type of natural cement is Pozzolanic (or Pozzuolanic) cement.

Portland cement is made by kiln-firing limestone to produce "clinker," which is then pulverized to produce fine, cementicious particles. In a concrete or mortar made with Portland cement, the cement particles are generally the smallest particles (although the Portland cement particles are large compared to fly ash). The Portland cement particles are extremely angular, due to the crushing action during manufacture.

Pozzolanic (or Pozzuolanic) cement has been used since the days of the Roman Empire. In Roman times, the cement was made from volcanic ash taken from the island of Pozzoli (also spelled Pozzuoli, hence the two spellings of the cement's name). In modern times, Pozzolanic cement is made from fly ash, which is a waste product from

Times	Third-Party Lab Results		Minimum Specifications	ASTM Standard
	PaveMend™ 5.0	*PaveMend*™ 15.0		
Compressive Strength				
1 hour	3330 psi	2700 psi	N/A	C 109
3 hours	3830 psi	3830 psi	1000 psi	C 109
1 day (24 hours)	5060 psi	4230 psi	3000 psi	C 109
7 days	6030 psi	5570 psi	4000 psi	C 109
28 days	6100 psi	6300 psi	≥ 7 day result	C 109
Bond Strength				
1 day (24 hours)	1970 psi	—	1000 psi	C 882
7 days	2780 psi	—	1500 psi	C 882
Flexural Strength				
7 days	700 psi	680 psi	—	C 78
28 days	930 psi	910 psi		C 78
Splitting Tensile Strength				
7 days	290 psi	240 psi	—	C 496
28 days	330 psi	345 psi	—	C 496
Scaling resistance, lb/ft^2				
25 cycles	0	0	Max 1.0 lb/ft^2 @ 25 cycles	C 672
Modulus of Elasticity, million psi				
—	3.4	3.3	—	C 469
Length Change, %				
28 days	+ 0.11 (soak) + 0.096 (dry)	+ 0.15 (soak) – 0.15 (dry)	—	C 157

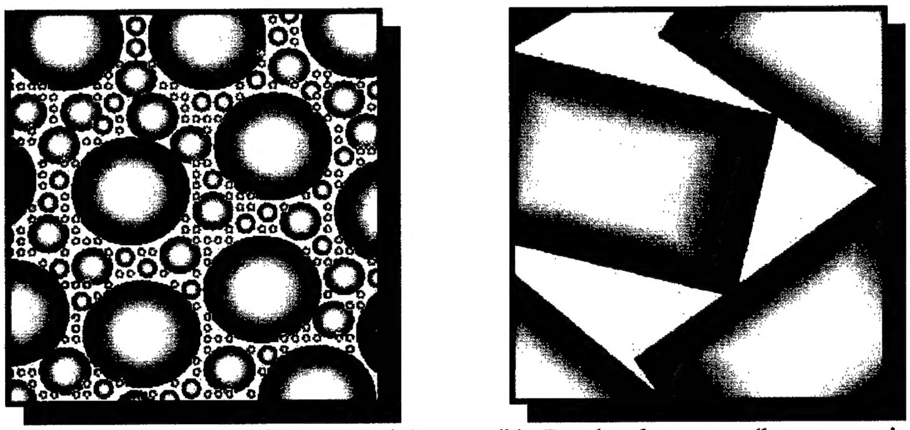
Table 2. Manufacturer's specification sheet for *PaveMend*™ RRR formulation.

the burning of coal (primarily from coal-fired utility plants). In the past, fly ash was released into the atmosphere via smoke stacks, but recent environmental regulations require collection and proper disposal of the fly ash (most often, into landfills). The combination of the ready availability of fly ash and a need for cements with improved properties for special tasks (such as RRR) created an environment that led to a product,

PaveMend™, that utilizes the special properties of fly ash to create a high-strength, rapid-set material.

Fly ash properties. Fly ash particles are spherical, and vary in size due to a phenomenon similar to the formation of hail (although the fly ash spheroids are composed mainly of SiO_2). Minuscule particles fly off the burning coal in minute molten bits that form round, glass balls as they tumble through the air. The heat waves cause more bits of molten glass to be carried upwards, some of which collide with other bits and become larger bits of molten glass that then tumble to form larger spheres. This process can continue with larger and larger spheres, until there are a wide variety of diameters of spheres. The glass spheroids are mainly composed of SiO_2, but have a number of other constituents, depending on the purity/impurity of the coal being burned.

The effect of fly ash on density. When considered independently from all other factors, rounded, poorly-graded particles (like fly ash), tend to form a denser matrix than angular, well-graded particles (like Portland cement). This phenomenon is illustrated in Figure 3.



(a) Pozzolanic cement (dense matrix) (b) Portland cement (loose matrix)

Figure 3. Artist's conceptual view of matrices for two main cement types

The rounded shape of the fly ash particles also contributes indirectly to improved density through "workability." In a mix, the fly ash spheroids act as little "ball bearings" which make the mix workable (i.e., easy to mix and pour). In a Portland cement concrete mix, extra mix water (in addition to the water needed for the cement reaction) is almost always added for workability. This extra water tends to push the particles apart even more, which in turn creates void spaces between particles in the finished product.

Regardless of the mechanism of creating voids in concrete, the void spaces tend to form small, interconnected "tunnels" which attract nearby water by a phenomenon known as capillary action (similar to capillary action in small blood vessels). This, in turn, causes long-term durability problems that are an almost direct consequence of having extra water in the concrete mix. For example, in colder climates the action of freezing and thawing causes breakdown of the matrix (i.e., freeze-thaw reaction). Conversely, extreme heat can cause water within the concrete matrix to be rapidly converted to steam that, in turn, causes a phenomenon similar to an explosion (i.e., breakout).

Pozzolanic cements, which create denser matrices than Portland cements, generally have increased density, a corresponding reduction in permeability and shrinkage, and a corresponding increase in durability. (This is the major reason that portions of Roman chariot roads survive today, still in relatively good condition.)

Advantages of PaveMend™ as a RRR material. Table 3 lists differences between

	PaveMend™	Typical commercially available RRR material
Surface Preparation	Requires little or no surface preparation	Requires extensive surface preparation (scarifying, etc.)
Curing Temperature	Cures over a wide range of surrounding temperature	Requires narrow range of ambient conditions for curing and designed set times.
Strength and Durability	No compromise of physical characteristics when rapid set time is required	Mixtures having quicker set time exhibit reduced durability
Setting Time	Fast setting in 20-30 minutes or less	One hour or more set time
Reduced Curing Time	1-3 hours between pouring and aircraft loading. Material is "self healing" during early curing, and can handle premature and/or excessive early loading, with full traffic reintroduced within 1-3 hours.	3-24 hours between pouring and loading. Material usually cracks from premature and/or excessive early loading.
Self-Leveling	Product flows / penetrates cracks. In its "liquid" state, it will "self-level."	Unpredictable leveling qualities
Aggregate Usage*	Much less effect from poor aggregate quality	Heavily dependent on specific quality / costly aggregates.
Admixtures	Does not require admixtures	Requires costly admixtures to control setting and physical characteristics.
Ease of Use	Extremely user friendly. Does not require exact water-dry mix ratio, etc.	Requires precise preparation and handling especially water content
Safety in Use	Worker-safe material. Does not emit toxic and/or obnoxious fumes or cause burns when prepared	Some available materials emit toxic and/or obnoxious fumes when prepared and some can cause caustic burns.
Flexibility	The mix design can easily be tailored for a wide range of applications and conditions	Rigid usage boundaries within the same mix design with regard to set time, application, etc.
Recycled Content	Contains high content of recycled materials. Can use indigenous raw materials.	Contains little or no recycled materials
Flexible Water Use	In some cases, certain non potable water can be used for mixtures	Requires drinking water quality for mixtures.
Reduced emissions in manufacturing	Contains no Portland cement (therefore reduces greenhouse gas emissions)	Contains Portland cement, which is a major source of greenhouse gas emissions.
Energy Reduction	Low energy consumer	Contains Portland cement, which comes from high-energy use production.

* *PaveMend*™ does not require aggregate, but may be used with aggregate – and, if used, *PaveMend*™ is extremely tolerant of aggregates with poor qualities

Table 3. *PaveMend*™ compared to a typical, commercially-available RRR material

PaveMend™ and a generic, typical RRR material. While no specific "traditional" product is named in Table 3, all of the data in Table 3 is based on manufacturer's literature.

Results of AFRL testing

Density. Figure 4 shows the results of density measurements on *PaveMend*™ and a Portland cement mortar mix. In addition, a typical Portland cement concrete (PCC) density is also shown. As can be seen from Figure 4, the *PaveMend*™ density is significantly greater that the cement mortar density, as expected, but the *PaveMend*™ mix has significantly lower density than a typical concrete mix. Therefore, since *PaveMend*™ does not require the use of (heavy) aggregates, it can be used as a lightweight alternative to PCC (even though it is much more dense than cement mortar).

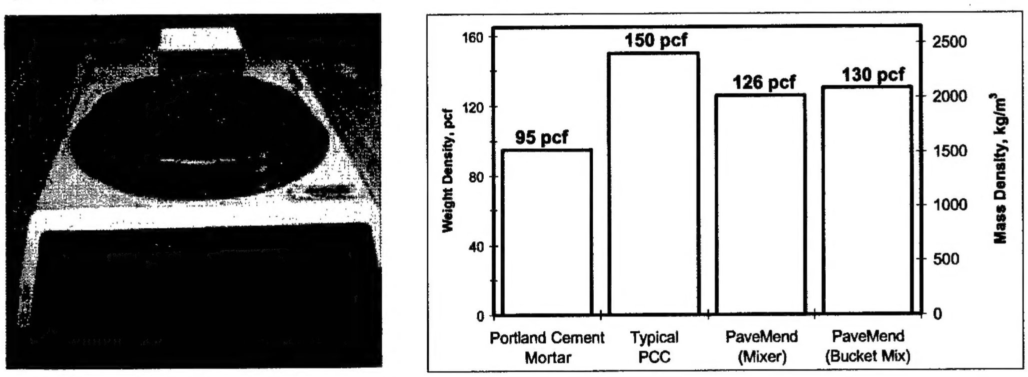


Figure 4. Results of AFRL Density measurements

Heat of Hydration. Figure 5 shows the results of AFRL temperature measurements. The *PaveMend*™ sample peaked at 77°C (170°F). Although that is hot to the touch, it is at a level which would be considered "manageable," and far lower than a typical high-early strength concrete.

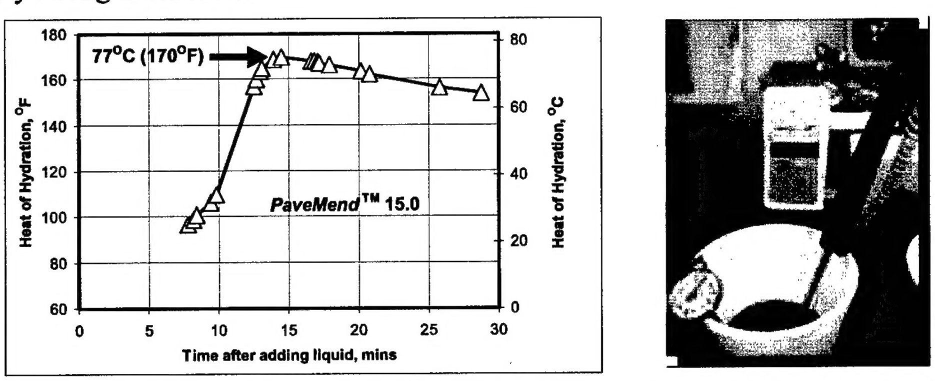


Figure 5. Results of AFRL Heat of Hydration measurements

Compressive Strength. Figures 6 and 7 show the results of AFRL compressive strength data. The data is the same in both figures, except that in Figure 6, the time scale is increased to show the early portion of the curve. In just a few hours, *PaveMend*™ had strength of 28-Mpa (4 ksi), which approximates a fully-cured, pavement quality concrete.

Flexural Strength. Figure 8 shows AFRL results from flexural strength tests. It is clear that *PaveMend*™ has high-early flexural strength (although there is some scatter in the data). This property is probably even more important for RRR than for other types of repairs, due to the tendency of heavy aircraft tires to put runway slabs into tension.

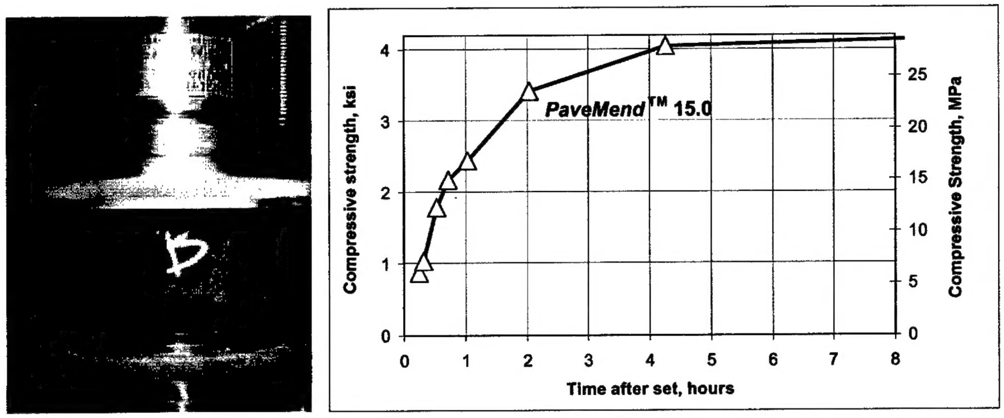


Figure 6. Results of AFRL Compressive Strength tests (early strength)

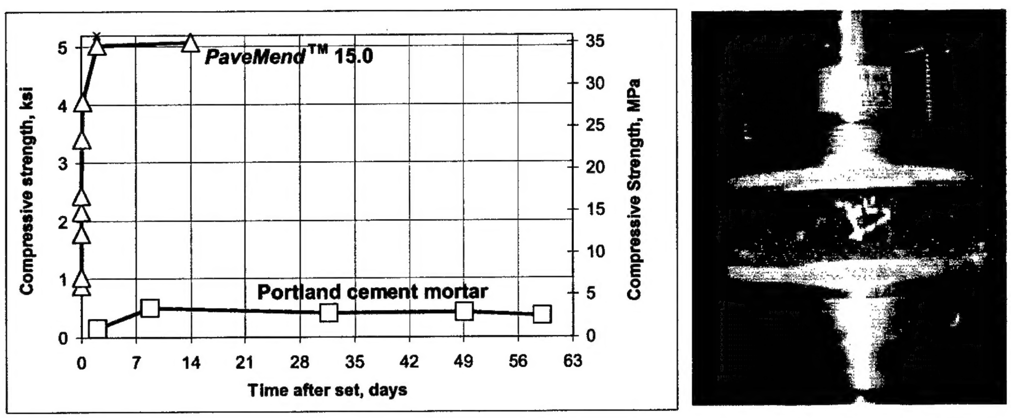


Figure 7. Results of AFRL Compressive Strength tests (ultimate strength)

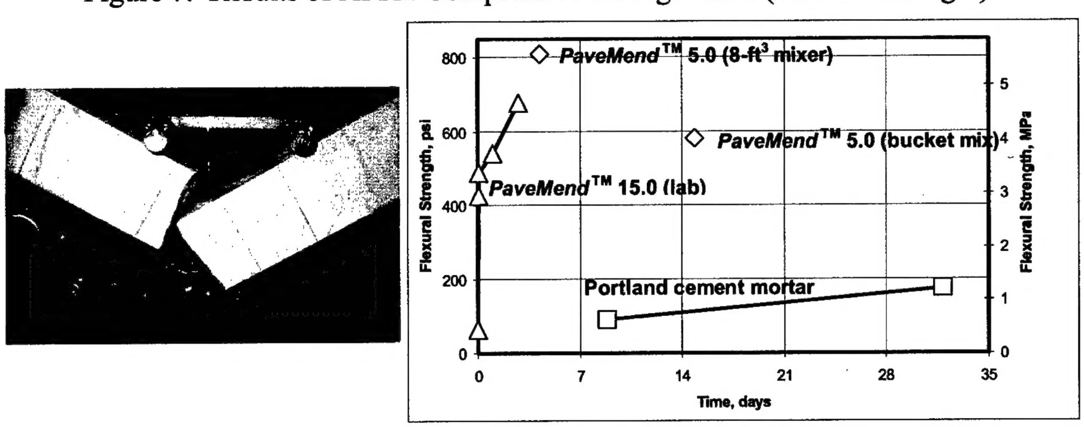


Figure 8. Results of AFRL Flexural Strength tests

Sonic Modulus of Elasticity. Figure 9 shows the results of AFRL sonic modulus tests. The *PaveMend*™ modulus jumps almost immediately to a modulus similar to that expected for a fully-cured runway pavement, and holds at approximately that level.

Bonding Strength. Figure 10 shows the results of AFRL bonding strength tests (also sometimes called the "slant shear" test). Virtually all *PaveMend*™ samples broke in a columnar fashion, indicating that the bond strength was greater than the strength of the PCC blanks used in the test (i.e., the sample approximated a monolithic structure).

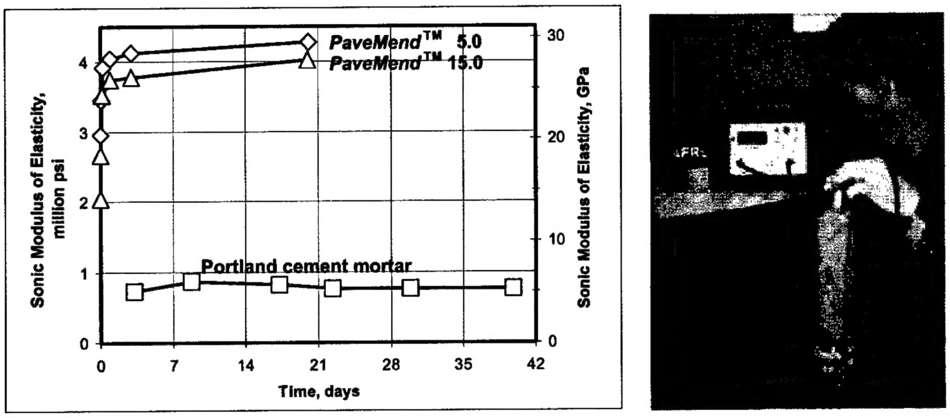


Figure 9. Results of AFRL Sonic Modulus of Elasticity tests

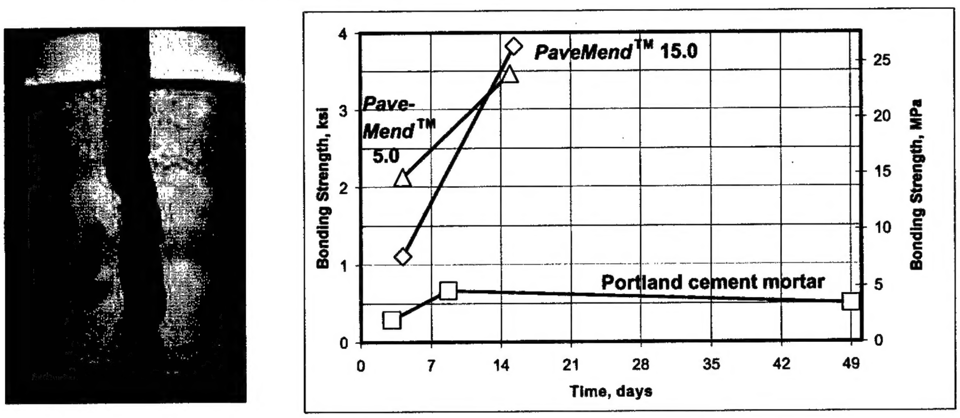


Figure 10. Results of AFRL Bonding Strength tests

Field Demonstration

CeraTech, Inc. held a full-scale demonstration at a site near Baltimore, Maryland, on 14 March 2002. In the demonstration, two simulated craters and an area with significant spalling were repaired with *PaveMend*™. The repairs were loaded with a backhoe (single wheel load approximately 2700 kg (3 tons)) after 1 hour and showed no ill effects, whatsoever.

Conclusions

While more research is needed, based on preliminary laboratory tests, and also based on the field demonstration, it would appear that *PaveMend*™ is an almost ideal material for RRR. *PaveMend*™ has a dense matrix, high-early compressive strength, high-early flexural strength, high-early modulus, and excellent bonding to fully-cured concrete. In addition, the RRR formulation of *PaveMend*™ has properties that are very close to those expected from the runways to be repaired. All this seems to add up to the two key ingredients needed for post-Cold War RRR, i.e., speed and durability.

References

Dover, Maj. Dov; Anderson, Dr. Mark; and Brown, Dr. Randall W., *Recent Advances in Matting Technology for Military Runways,* Proceedings, ASCE Air Transport Conference, 2002.